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Liquid Cooling of Non-Uniform Heat flux of Chip Circuit by Submicrochannels

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Abstract - Sumbmicrochannels have been placed on the hotspots in a non-uniform heat generated chip circuit to increase the liquid/solid interaction area and then to enhance the heat dissipation. Main microchannels width is 185µm, which is twice the width of the submicrochannels and also includes the wall thickness of 35µm, and wall height is 500µm. The chip dimension is 10mm×10mm and the hotspot is 4mm×10m. Different positions of the hotspot have been investigated e.g. upstream, middle and downstream. Uniform heat flux is 100W/cm^2 while for the hot spot is 150 W/cm^2. Single channel simulation reveals that the downstream hotspot gives a lower temperature of the chip circuit surface; however the upstream hotspot has more uniform temperature distribution. A special design of manifold was adopted to ensure an equal mass distribution through the microchannels.

***Keywords*—Chip circuit, nonuniform heat flux, submicrochannels, CFD**

I. Introduction

The main purpose of using microchannels in [1] was to remove the maximum amount of heat generated from a limited space. This technology was also used to remove uniform heat generated from integrated circuits [1-3]. But due to a non-uniform heat dissipation from electronic circuits, hotspots are generated as shown in [4, 5]. Parallel microchannels have been used in [6, 7] to reduce the uniform and non-uniform heat flux distributions, but due to an unequal flow rate through the microchannels, the non-uniform temperature distribution was generated. Therefore, different design approaches were developed to extract more the high heat flux of the hotspots.

Locations and amounts of heat generated at the hotspot on a chip surface decide the design of microchannels to efficiently get the uniform temperature distributions. Two-layer heat sink was attached to the chip surface in [8] which generates a variable heat flux along the microchannels. Additionally, a counter fluid flow through the channels gave more uniform temperature distribution along the surface with the heat flux increasing or decreasing along the microchannels.

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Chauhan [4] used another approach for redistributing the hotspot locations to get a uniform heat flux above the chip circuit. Changing the flow direction where the cold fluid meets the hotspot at the entrance or in the opposite direction, Chauhan tried the counter flow between two adjacent microchannels and the results showed that placing hotspots at the inlet gave more cooling action.

Zhang [5] divided the chip into the low and high heat flux areas and reduced the width of the channel above the hotspots to minimise the temperature. Minliang [9] and Wang [10] followed the same procedure by narrowing the microchannels width above the hotspot to increase the fluid-solid interaction area.

In this work the main microchannles have been divided into two submicrochannels above the hotspot by adding additional walls at the middle of the channels. Three positions of hotspot are tested: upstream, middle, and downstream of the flow with respect to the flow through microchannels. A special design of manifold has been adopted to ensure an equal distribution of mass flow through the microchannels.

II. Mathematical modelling

Flows through microchannels have been considered to be incompressible, single-phase, steady-state and laminar. Continuity and Navier-Stokes equations (1)-(4) governing the flow field in 3D microchannels are written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (3)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (4)$$

where u, v, and w are the velocity components along the x, y, and w directions respectively. ρ, P, and ν are the fluid density, pressure and kinematics viscosity, respectively.

Energy equation (5) has been solved to analyse the thermal interaction between the microchannels and water liquid.

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial x}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (5)$$

Thermal resistance R_o is calculated from the following equations [11]

$$R_o=\frac{\Delta T_{max}}{q_1^{"}\times A_1+q_2^{"}\times A_{spot}} \quad (6)$$

$$\Delta T_{max}=T_{w,o}-T_{f,i} \quad (7)$$

where $T_{w,o}$ is the peak temperature of the chip surface, $T_{f,i}$, is the fluid inlet temperature, $A_1$is the uniform heat flux surface area [m^2], A_{spot} is the hot spot surface area, $q_1^{"}$ is the background heat flux [W/m^2], and $q_1^{"}$ is the hotspot heat flux [W/m^2].

III. Heat sink design

A. *Design of microchannels*

Minimisation of pumping and thermal resistance is the main objective for the design of microchannels which are usually affected by the several system parameters such as channel height, channel width and wall thickness, as well as by the applied hydraulic and thermal boundary conditions [12, 13].

In the present work heat sink has been designed using parallel microchannels to cool the uniform heat generated at the chip surface, while the submicrochannels were added on the hot spots, "Fig. 1". Effects of three locations of hotspot have been investigated: upstream, middle and downstream. Submicrochannels have been proposed by Koo [14] to decrease the single-phase temperature in a two-phase flow cooling of non-uniform heat generated from a chip circuit.

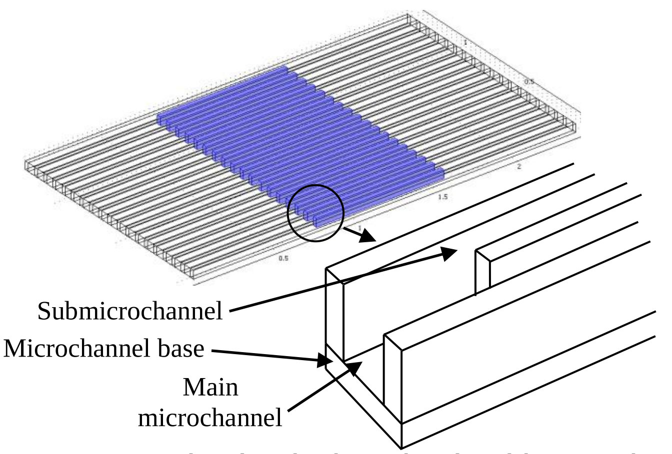

Fig. 1 3D microchannels with submicrochannels and hotspot at the middle position.

Chip dimension is 10mm×10mm whereas the length of the inlet and outlet manifold is equal to 4mm. Therefore, the total dimension of the chip is 18mm×10mm including the manifolds. Submicrochhannel dimensions are 500µm, 75µm, and 35µm for the channel height, channel width, and wall thickness respectively. The main microchannel has the same height as the submicrohannels but its width is doubled and equal to 185µm (including wall thickness) and the base thickness is set to 100 µm. Hotspot dimension is 4mm in length and it has the same width of the chip, which is 10mm.

B. *Manifold design*

Manifold design highly affects the temperature uniformity of the chip circuit due to the equal flow rate distribution. Different design methodology has been investigated in order to get a uniform volume flow distribution. Inlet flow conditions will also affect the flow distribution in the microchannels, as shown in Solovitz & Mainka [15]. They designed different manifolds depending on the equal pressure drop through the inlet and outlet manifolds and microchannels. Their results showed that an increase in the inlet Reynolds number alters the flow rate through microchannels which also depends on the different designs of the manifold. Rectangular maicorchannels with different inlet and outlet locations couldn't improve the uniformity of flow through micorchannels [16].

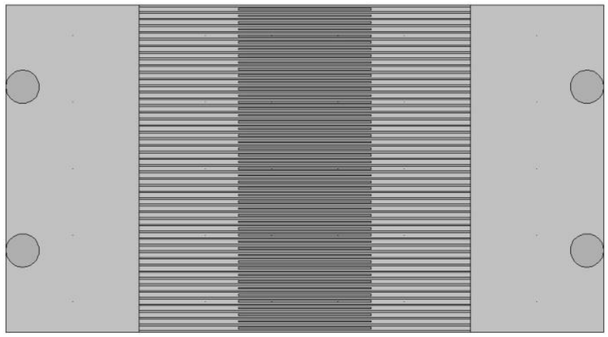

Fig. 2 2D geometry of the microchannels with two inlets and two outlets.

A special design of the manifold has been investigated in order to get an approximately equal flow rate distribution through the microchannels, see "Fig. 2" and "Fig. 3".

Results in "Fig. 3" show a uniform temperature distribution at the chip surface. Boundary condition for the total inlet volume rate is equal to $6.28\times10^{-3}m^3/s$ which leads to an average velocity of 1.4 m/s in each microchannel. Inlet temperature equals to 20^oC, background heat flux equals to 100 kW/m^2, and the hotspot heat flux equals to 150 kW/m^2.

IV. Numerical simulation

Numerical simulation has been performed with the commercial software COMSOL3.5a for a single microchannel with an assumption of the equal flow rate distributing through each microchannel (see $III.BIII).

Hydraulic and thermal boundary conditions are shown in "Fig. 4" which represents a single channel model. Micorchannel material is silicone with properties: thermal conductivity 163 [W/(m K)], density 2330[kg/m^3], and heat capacity at constant pressure 703 [J/(kg K)].

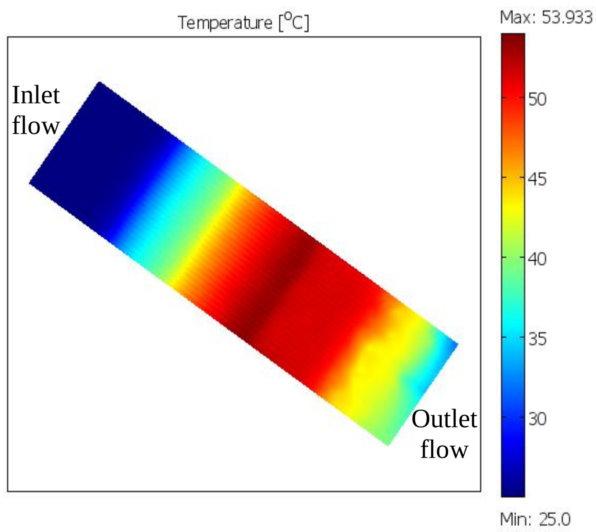

Fig. 3 2D Temperature distribution on the chip surface (half geometry model).

Different densities of the heat flux (200 W/m^2 to 500W/m^2) at the middle location have been studied.

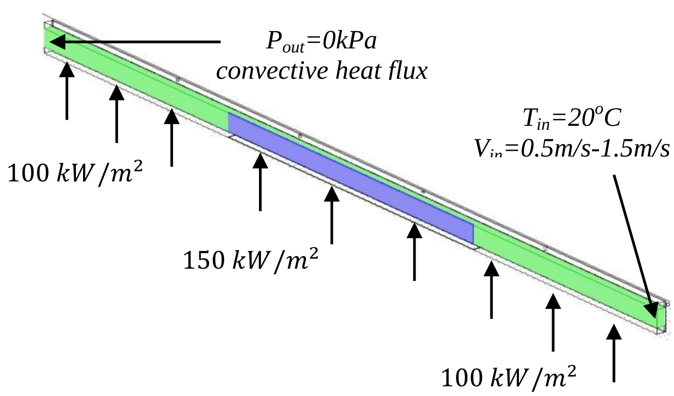

Fig. 4 3D Half geometry of a single microchannel with boundary conditions

V. Results and discussion

Heat transfer increases by adding the submicrochannels due to the increase in the interaction area between the solid and liquids. Moreover, a reduction in the channel width augmented the Nusselt number and consequently the convection heat transfer [17]. This improvement was followed by an increase in the pressure drop as shown in “Fig. 5”. For a constant pumping power the effect of inserting submicrochannels leads to an increase in the pressure drop but at the same time the thermal resistance decreases, see “Fig. 6”.

“Fig. 7” shows a comparison between the effect of the three locations of the hot spot and the submicrochannel on the pressure drop and pumping power. It is obvious that there is a negligible effect of the sumicrochannels on the pressure drop.

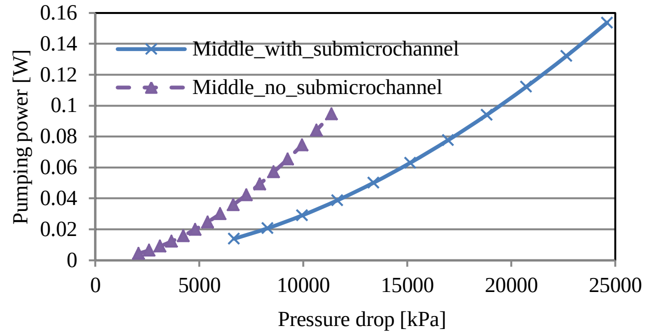

Fig. 5 Comparison between the pressure drop and pumping power with and without submicrochannel for hotspot at the middle position.

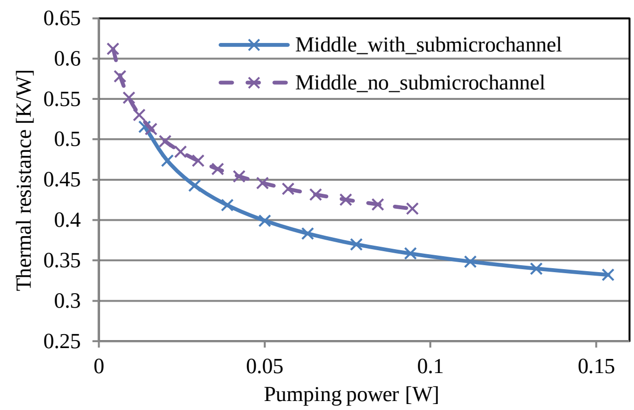

Fig. 6 Comparison between the thermal resistance and pumping power with and without submicrochannel for hotspot at the middle position.

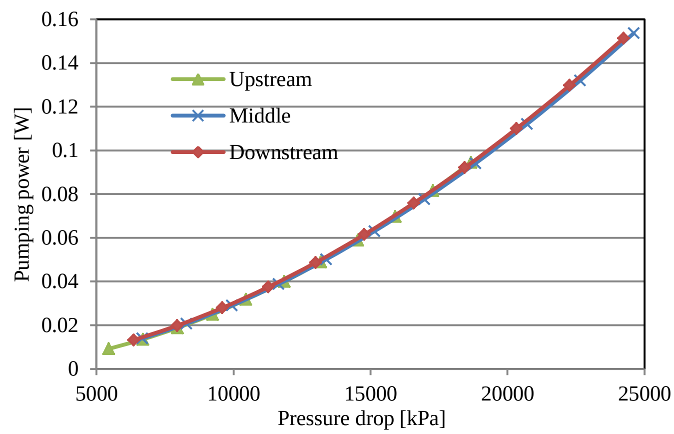

Fig. 7 Comparison of the pressure drop and pumping power with submicrochannels for different hotspot positions.

Hot spot at the downstream of the flow gave a better thermal resistance compared with that at the middle and upstream locations as shown in “Fig. 8” and “Fig. 9”. For a constant pressure drop (or a pumping power) the downstream hotspot gives a lower thermal resistance. However, when the water flows over and around the upstream (or middle) hotspots, its temperature rises. Therefore, when water is flowing out of submicrochannels, with higher temperature, to the main microchannels will has lower cooling capacity.

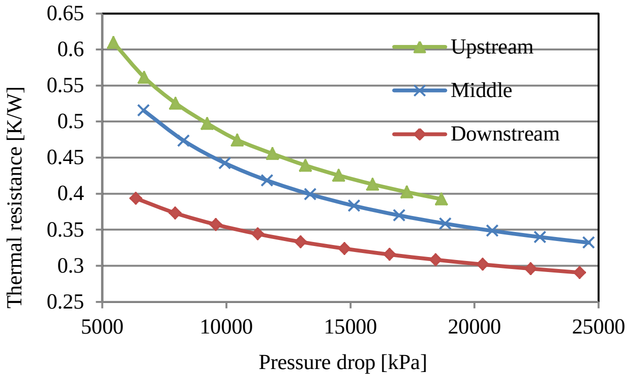

Fig. 8 Comparison between the pressure drop and thermal resistance with submicrochannels for different hotspot positions.

Consequently, the middle hotspot has a lower thermal resistance compared with that in the upstream hotspot.

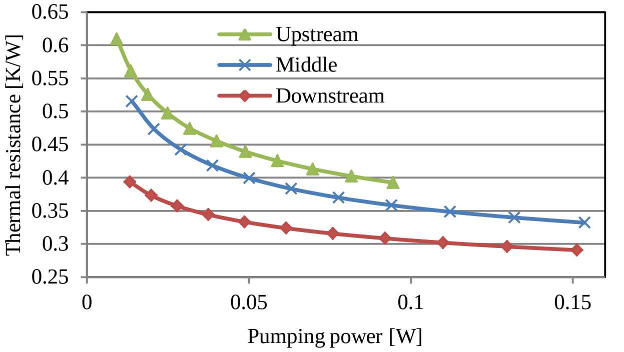

Fig. 9 Comparison between the pumping power and thermal resistance with submicrochannels for hotspot positions.

Downstream hot spot gives lower chip surface temperature surface at the outlet as shown in “Fig. 10” while the middle hotspot position has a lower temperature along the surface. Furthermore, the upstream hot spot has more uniform temperature distribution.

Effect of the higher heat fluxes at the middle hot spot on the chip surface temperature has been studied as shown in *Error! Reference source not found.*. Simulation results show that the temperature is still within acceptable limit [18], even the increasing in heat flux to five times of the uniform heat flux.

VI. Conclusions

High heat flux generated at the hot spots on the chip surface has been extracted by adding submicrochannels. Main microchannels were used to remove the background uniform heat flux while their widths were narrowed above the hotpots by inserting additional fins which divided into the two narrow channels. Three different locations of the hot spots were studied: upstream, middle, and downstream.

The results show good improvements in the temperature distributions along the chip surface. Downstream positions give lower thermal resistance and temperature in comparison with upstream and middle locations. However, the upstream hotspot gave more uniform temperature. Pressure drop increases by inserting the submicrochannels in comparison without them. But the submicrochannels position has negligible effect on the pressure drop. Effect of increasing heat flux density at hot spot, with the same microchannels and submicorchannels sizes, on the chip temperature is still within an acceptable range.

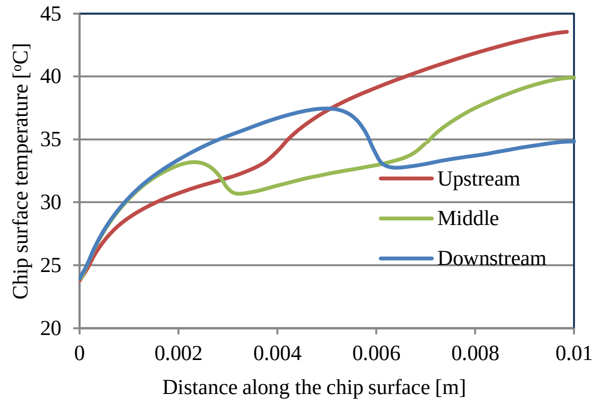

Fig. 10 Chip surface temperature with constant inlet velocity 1.5[m/s] with different hot spot position.

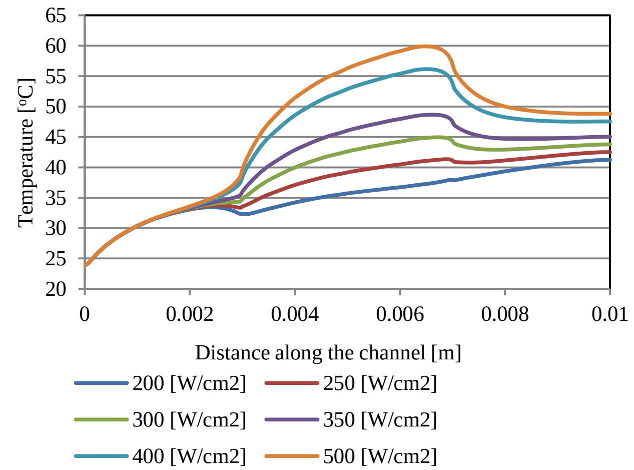

Fig. 11 Temperature distribution along the chip surface for different density of heat flux at middle position of hotspot with inlet velocity 1.5[m/s].

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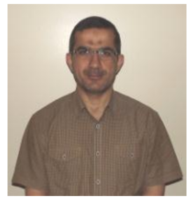

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